Design and construction of the Barriga Dam spillway through an improved wedge-shaped block technology

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Abstract: The Barriga Dam (Burgos, Spain) is a unique case study because its trapezoid spillway is located on the dam body and is composed of wedge-shaped concrete blocks (WSB) that include certain relevant improvements. This note summarizes the main features of the studies, the key aspects of the final design of the WSB and their placement on the dam, and important details of the spillway design. The design team concluded the study by showing the suitability of this enhanced technology for application to small dams and ponds in the short term, even with unit flows above 5 m²/s.

Key words: dams, spillways, wedge-shaped blocks, precast concrete, overtopping, erosion, protections.

Résumé : Le barrage Barriga (Burgos, Espagne) est une étude de cas unique, car son déversoir trapézoïdal est situé sur le corps du barrage et est composé de blocs de béton en forme de coin (« WSB ») qui comprennent certaines améliorations pertinentes. Cette note résume les principales caractéristiques des études, les aspects clés de la conception finale de la WSB et leur placement sur le barrage, et les détails importants de la conception du déversoir. L'équipe de conception a terminé l'étude en montrant la pertinence de cette technologie améliorée pour l'application, à court terme, à de petits barrages et plans d'eau, même avec des débits unitaires supérieurs à 5 m²/s. [Traduit par le Rédaction]

Mots-clés : barrages, déversoirs, blocs en forme de coin, béton préfabriqué, débordement, érosion, protections.

Introduction

The Barriga Dam was constructed for irrigation purposes in the Valle de Losa region (Burgos), in the north of Spain (Fig. 1). The project was funded by the Junta de Castilla y León regional government. The dam is located in the Nabón Creek and the area of the drainage basin is 20 km². The reservoir capacity is 0.5 hm³ and the maximum height of the dam 17 m.

To design the spillway, a flow capacity of 161 m³/s (8.0 m²/s) was considered, whereas an extreme flood flow of 229 m³/s (11.4 m²/s) was estimated as a limit scenario. The project was concluded in 2006 and the spillway successfully passed two floods with peak unit flows up to 0.5 m²/s.

In a WSB spillway, the usual reinforced concrete slab is replaced by a revetment that consists of overlapped precast concrete blocks. As every block overlaps the next downstream one, the revetment constitutes a stepped spillway. The stability of each block is assured by the positive pressure of the water on the upper face, overlapping from adjacent blocks and the negative pressure of air on its lower face. The vents, located in the lower zone of the step riser, transfer the negative pressure to the surface between the block and the bedding layer, which means that the ensuing suction enhances the stability of the block.

Most of the cases of WSB spillways prior to the Barriga Dam project were prototype facilities. The most important were in Bolshevik, Klinbeldin, Maslovo, Sosnovski, the Dnieper Hydropower Dam, Dneister, Kolyma, Transbaikal, and Jelyevski in Russia; Jiangshe Wanan in China; and Wadi Sahalnawt in Oman (Hewlett et al. 1997). After construction of the Barriga Dam, the Bruton Dam WSB spillway was built in Somerset, United Kingdom (Pether et al. 2009).

Block design

The design and manufacture of the blocks took place during the construction of the dam. The final design was based on the standard Armorwedge™ block, though significant changes were made. The Armorwedge™ block was the unit that was tested in the physical models performed at Colorado State University (CSU) for the Barriga Dam spillway (Thornton et al. 2006). The changes implemented aimed to increase the general safety of the dam. The scale factor used to size the blocks for the Barriga Dam was based on the tests made by CSU Laboratório Nacional de Engenharia Civil (LNEC).

The standard block size was tested in the flume up to the flume discharge capacity (4.8 m³/s, e.g., 4.7 m²/s per unit-width). The block sizes were then scaled up to produce a block with the geometry, thickness, weight, and strength required to meet the flow requirements for the Barriga Dam and the safety level needed with regard to vandalism, durability, impact resistance, and constructability issues that are not scalable.

An interior hole was added transversely to the block (Fig. 2) to allow a cable to be introduced into the hole to join each WSB with the others in the same row. This made it more difficult for the blocks to be pulled out of the revetment due to unforeseen causes. In addition, this hole provides assistance in the transportation and placement of the blocks. The concrete compressive strength was increased up to 50 N/mm² to improve the impact behavior. The main differences between the standard Armorwedge™ unit and the Barriga Dam WSB are shown in Table 1.

Spillway inlet

The spillway inlet comprises a smooth, curved transition between the reservoir and the trapezoidal chute (Fig. 3). The transverse slopes of the spillway inlet trapezoidal channel are $2H{:}1V$.

Fig. 1. Location of Barriga Dam.

Fig. 2. 3D view of the WSB at the Barriga Dam.

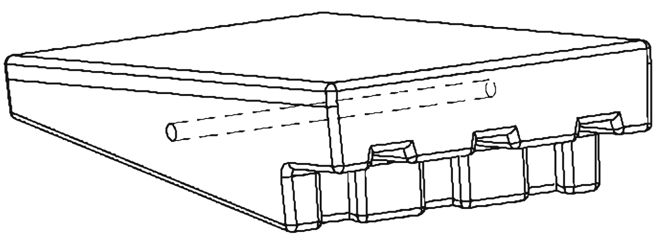

Table 1. Comparison between the Armorwedge unit and the Barriga Dam WSB.

	Armorwedge™ unit	Barriga Dam WSB
Maximum dimensions (cm)	45.7×30.4×13.0	73.0×50.0×20.0
Weight (kN)	0.22	1.09
Aeration vents	3 of 3.8×1.3 cm²	3 of 5.0×2.0 cm²
Type of concrete	Dry cast concrete with a 20 N/mm² compressive strength	Wet cast concrete with a 50 N/mm² compressive strength
Transverse hole	No	Yes; 22 mm diameter

Note: WSB, wedge-shaped concrete blocks.

The trapezoidal channel, slab and slopes, and transition zone, were constructed in reinforced concrete 0.4 m thick that was fixed to the dam body with a grid of 1 m bolts. The upstream end of this transition zone was used to anchor the impervious polyethylene blanket by extending it to approximately 10 m beneath the reinforced concrete structure.

The LNEC model (LNEC 2006) showed difficulties in controlling shockwaves with the original design and especially in avoiding flow concentration in the middle of the channel. With the modified design, the flow was uniformly distributed along the whole width of the trapezoidal channel so that the hydraulic conditions upstream of the WSB chute were significantly improved over those observed in the corresponding LNEC model tests.

Spillway chute

The spillway chute is placed on the dam body. The bottom of the chute, which is considered the upside plane of the WSB, is excavated in the downstream shoulder of the dam to a depth of 2 m. The slopes ($2H$:$1V$) of the chute are also protected with WSB.

The WSB chute starts at the end of the horizontal channel, which is rounded off with a vertical curve to join it to the chute slope ($2H$:$1V$); this is the same as the downstream slope of the dam. From this point, the WSB chute maintains this slope until its end, which is placed upstream of the ski jump concrete structure (Fig. 4). In the chute, the flow is highly aerated due to the steps that are formed by the rows of WSB.

The body of the Barriga Dam is formed by compacted limestone rockfill. Therefore, the ability of the dam body to drain the seepage flows coming from the spillway is assured. Thus, the next important issue was the maintenance of the internal stability of the materials beneath the blocks. To achieve this objective, two bedding layers were placed between the blocks and the dam body. Immediately below the blocks, a 20 cm drainage layer of crushed limestone was extended upon another 20 cm crushed limestone layer of transition material, which simultaneously fulfills the filter condition with respect to the dam body material and serves as the drainage layer. Both materials were designed to be internally stable, as defined by Sherard's criterion for the instability ratio.

The upstream joint between the chute and the inlet structure is located in a section where the velocity of the spillway flow is still low. Therefore, the stabilization forces due to the negative pressures that develop in the steps are still negligible. Thus, the adopted solution was an extension of the reinforced concrete of the inlet channel that overlaps the first row of WSB, as a theoretical upstream row of blocks would do.

The downstream joint represents the border between the first row of WSB, which is downstream from the chute, and the ski jump structure. Given that this is the first row of WSB to be placed, its correct positioning is a key factor to position the rest of the rows properly. Proper placement of this row is also important because the upstream rows of WSB rest over the first one; failure

Fig. 3. Plan view of the Barriga Dam's spillway.

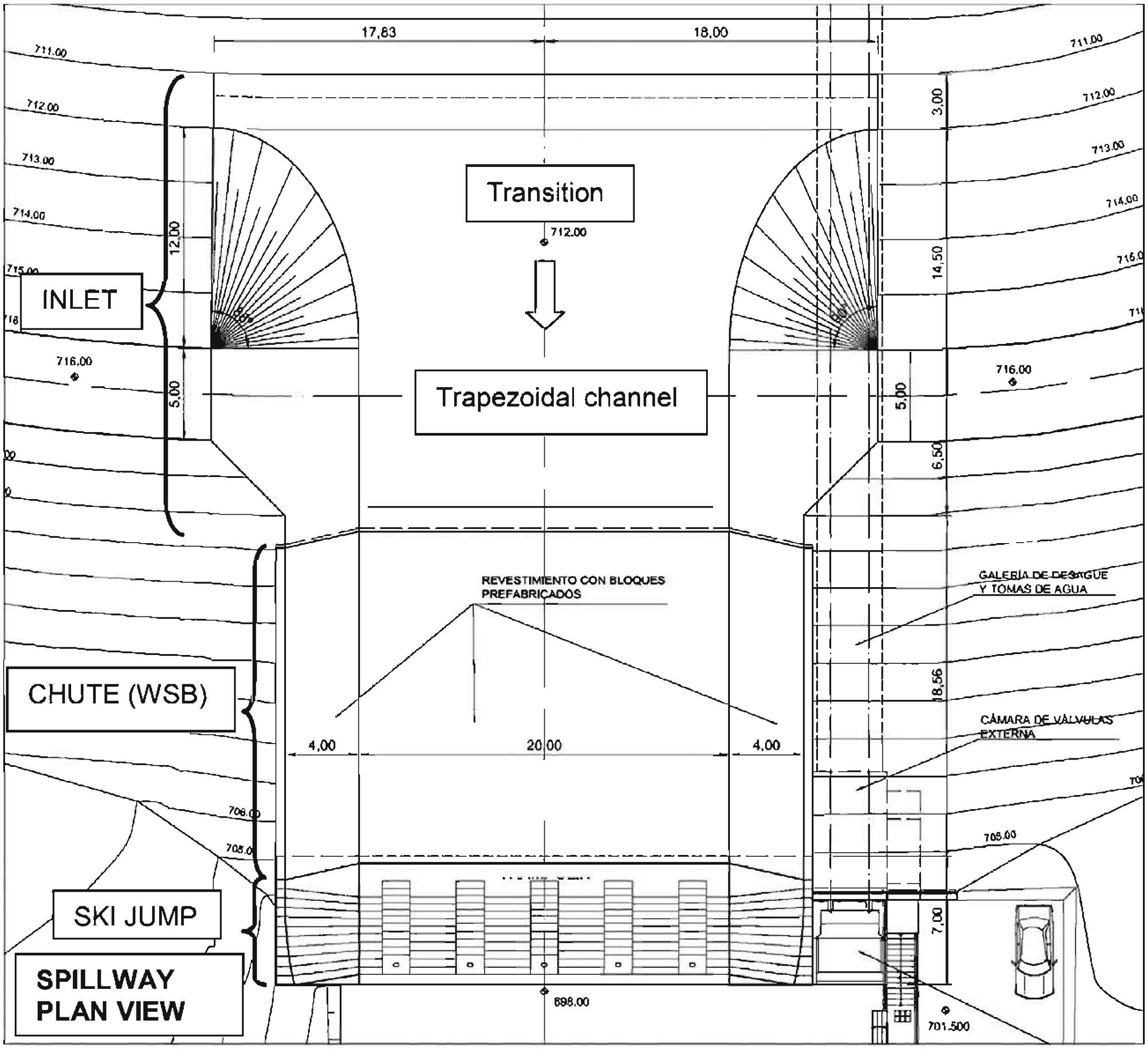

Fig. 4. View of the spillway from downstream left overbank.

to position this first row correctly would have serious consequences for the remainder of the spillway. The adopted solution was to place the first row of WSB resting on a notch at the edge of the ski jump structure filled with cement mortar.

Intermediate joints are the unions between the left and right slopes and the bottom of the chute. After studying several alternatives, the project team decided to adopt a joint that conserved the geometry of the converging rows, which also resulted in a stepped joint. The joints were built after the construction of the converging rows and were useful for placing the anchors of the cable lines. The gap between WSB was filled with structural concrete. Reinforcing steel bars were added all along and contraction joints were implemented every 3 m.

Ski jump structure

The solution selected to restore the spillway flow to the river bed was a ski jump. This type of mass concrete structure was originally conceived by Álvarez et al. (1998). The ski jump is located at the end of the spillway chute and is composed of two lateral structures on both river banks and four parallelepiped blocks with dimensions of 1.8 m (width) × 7.0 m (length) × 4.0 m (height) in the river bed (Fig. 4). The gaps between these blocks

(2 m wide and 4 m high) are filled with large stones (minimum size of 0.8 m). The ski jump is placed above this concrete mass structure. The radius of the ski jump is 4.45 m, and the exit angle is 30°. Additionally, there are five baffle blocks with a radius of 3.68 m and an exit angle of 45°. These baffle blocks are provided with aerators on the downstream face.

The main reasons behind the choice of this solution were the following:

(*a*) The good quality of the foundation in the river bed;

(*b*) This approach allowed complete separation between the WSB chute and the downstream water level. Thus, the WSB did not have to bear the turbulent and transient flows produced in the energy dissipation zone.

(*c*) Drainage of the dam body material was assessed through the gaps between concrete mass blocks even in extreme flooding situations.

(*d*) The lateral convergence designed in the ski jump avoided the possibility of erosion occurring at both banks of the river. This level of stream–bank protection was verified in the results of the LNEC model testing program.

Conclusions and future research

The work performed in the design and construction of the Barriga Dam spillway has enabled the identification of the main problems with this type of technology. It was necessary to examine the manufacturing process of the WSB, materials, quality control, commissioning work, design of the block supporting layers, and joints between parts of the spillway.

The general conclusion is that WSB technology offers a good solution for the discharging of high flows over the body of embankment dams. Although this solution is necessarily limited in the scope of its application at the time of writing this note, an increased adoption of this type of spillway in the future can be expected.

Possible applications include the enlargement of the hydraulic capacity of spillways for extreme floods in existing dams; spillways for ponds without major natural inflows; and service spillways in dams of moderate size.

Research into this type of technology is still necessary for further expansion. Any proposed study should aim for the following:

1. A deeper understanding of the hydraulic behavior and the dependence of the shape and dimensions of WSB;
2. Optimization of shapes of WSB from a 'hydraulics' viewpoint;
3. Study of new materials or concrete additives to improve the mechanical behavior of the blocks.
4. In addition, design criteria about compatible energy dissipation structures and construction details should also be sought.

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